Journal of Engineering Physics and Thermophysics, Vol. 82, No. 1, 2009

EXPERIMENTAL STUDY OF THE HIGH-TEMPERATURE THERMOMECHANICAL DRYING OF WOOD

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UDC 674.047

The results of an experimental study of the thermomechanical drying of cylinder-shaped wood by the depressurization method are presented. The high rate of the process of thermomechanical drying with a good quality of dried articles has been confirmed.

Keywords: *drying, wood, depressurization, thermomechanical.*

Introduction. Thermal drying of wood is the most power- and time-consuming process of wood working. As investigations have shown [1], in drying green wood to an absolute humidity of 7–8%, the period of free moisture evaporation takes 60–80% of the entire period of the drying process and the remaining time is expended in removing hygroscopic moisture.

There exist methods for removing free moisture without expenditure of heat, e.g., by means of centrifugation. This process is particularly effective for dewatering wet (submerged) wood whose absolute humidity can amount to 170–180% (pine). Experiments on centrifugal dewatering of high-humidity pine have shown that to decrease the humidity by 50–100% the action of a centrifugal force field for 10–20 min suffices [2, 3].

M. Bentz and M. Stahl proposed a method of mechanical dewatering with the use of the incubation-decompression process (I/*D* process) [4]. The air injected through the pneumatic system into the cellular structure of wood dissolves in the wood juice during the incubation period and at the next stage, upon depressurization, in the process of decompression the air bubbles mechanically force out the liquid. In so doing, a dewatering rate of up to 7–10% per hour was attained. If instead of air in the I/*D* process a rapidly soluble gas, e.g., CO_2, which finds industrial application in the process of oil production [5], is used, then due to the rapid release of gas bubbles upon depressurization and the increase in the volume of the gas-liquid medium the efficiency of moisture removal increases.

A promising direction of improving the drying technology is the application of the thermomechanical method combining thermal and mechanical dewatering. The thermomechanical method of drying a material by the depressurization technique was first used by Fleissner in 1926 for drying coal [6]. With such a method, a humid material is preheated in a hermetic chamber with increasing pressure, and then upon quick depressurization in the bulk of the material there occurs rapid vaporization due to the accumulated heat. The molar vapor flow captures liquid particles, as a result of which the heat expenditure in drying markedly decreases. The heat energy of the gas-vapor flow is conveyed into another chamber for preheating the material with parallel operation of analogous devices.

Heat and mass transfer intensification in the thermomechanical drying of dispersed materials was noted in a number of works [7–10]. At the present time this technology is used in the cyclic vacuum drying of various materials in the range of pressures from 0.01 to 0.1 MPa and at temperatures of up to 100°C [11]. The use of high pressures is explained by the danger of failure of a material (especially a low-permeability one) under the action of the pressure drop and thermal stresses. Works are known in which hard modes of depressurization were used with the aim of communition of material [6].

In [12], it was shown that in the thermomechanical drying the moisture is most effectively removed from wood at pressures of 0.3–0.6 MPa and a temperature of up to 150°C. In so doing, high-quality drying was achieved. In [13], the possibility of high-temperature drying of wood in a variable-pressure medium of the drying agent without a decrease in the physicomechanical properties of wood was also noted.

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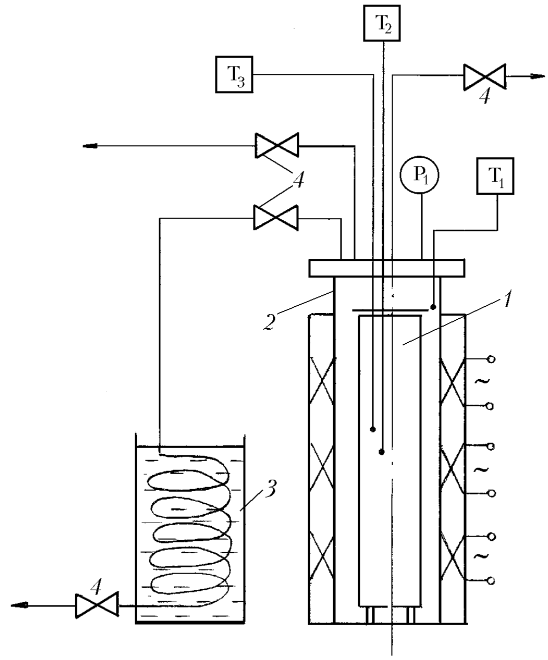


Fig. 1. Basic diagram of the facility: 1) cylindrical specimen of wood; 2) working cylinder with heaters; 3) condenser; 4) valves.

The goal of the present work is to use this technology for qualitative drying of wood. The choice of the drying conditions is aimed at intensifying the diffusion and molar transfer of vapor and liquid particles in pores, providing low moisture content gradients determining the drying quality. It should also be noted that under high-temperature conditions the plasticity and the water vapor and air permeability of wood increase, which also lowers the probability of drying defect formation [1, 14].

In the traditional convective drying of wood articles of large thicknesses or circular cross-section, to obtain the required quality, one has to spend much time. For example, for cylinder-shaped green pine of diameter 0.1 m the time of drying to an absolute humidity of 20% is 170–200 h.

Experimental Facility. The investigations aimed at estimating the efficiency of the thermomechanical method of drying cylinder-shaped wood with the use of the depressurization technique were carried out on the facility schematically represented in Fig. 1. The specimen is placed in a hermetic cylindrical vessel — a working cylinder of length 1 m and diameter 0.16 m. On the cylinder case, there are circular electric heaters. The pressure gauge P_1 and the temperature meters $T_1 - T_3$ serve to control the pressure and temperature in the cylinder and in the specimen. The valves make it possible to discharge the vapor and draw off the liquid from the vessel. The facility incorporates a system of pressure release through a cooled condenser coil or through a sputterer into a vessel with cold water. We recorded the temperature measurement data of the gaseous medium and of the working cylinder case, the temperature in the wood specimen, the mass of the vapor-fluid flow from the chamber, and the temperature of the cooling water in the condenser. The facility can be connected to a vacuum pump and a steam generator.

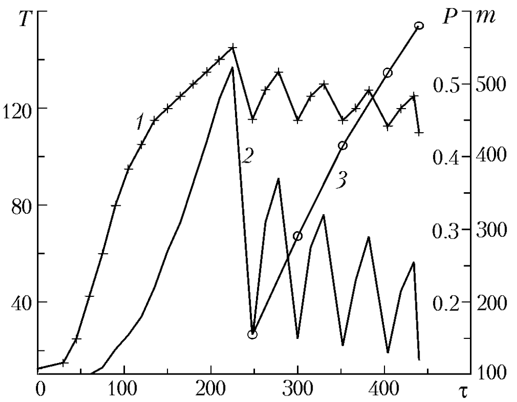
The process of thermomechanical drying included many stages, the main ones of which are:

1) cyclic heating of the material in the chamber (due to the radiative and convective heat exchange); in this process the wood was heated in steam with increasing pressure due to the moisture evaporation (condensation), which provided a decrease in internal stresses in the wood;

2) depressurization, at which intensive release of vapor and free moisture from the wood structure occurred;

3) drying with the aim of decreasing the bound moisture content W from 30% to 8–10% due to evaporation.

Vapor was condensed in the vapor collecting system where the liquid mass and the temperature were controlled. Upon completion of the drying and cooling process the specimen was weighed and then cut or split lengthwise into equal parts, and its humidity was measured by means of a humidity meter.



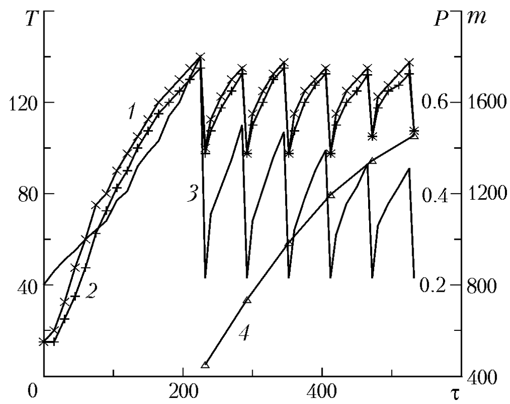


Fig. 2. Change in the temperature inside the specimen (1), in the chamber pressure (2), and in the removed moisture mass (3) at a periodic release of pressure (D = 0.08 m, W_0 = 47.3%, W_f = 4.0%). T, ^oC; P, MPa; m, g; τ, min.

Fig. 3. Change in the temperature inside the specimen at a depth of $r/2$ (1) and at the center (2), in the chamber pressure (3), and in the removed moisture mass (4) at a periodic release of pressure (D = 0.1 m, W_0 = 69.2%, W_f = 11.3%). T, ^oC; P, MPa; m, g; τ, min.

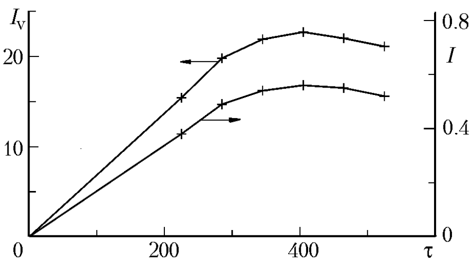
Experiments were conducted with cylindrical pine specimens of diameters 0.08 and 0.1 m and length up to 0.9 m. The drying quality was estimated by the presence and sizes of cracks on the surface and faces of the specimen upon completion of the drying process, the color of the surface, and by the moisture spread in the bulk of the wood.

Measurement Data. As was shown earlier in [12], the process of thermomechanical drying depends on many factors, the main of which are the temperature and pressure of the vapor-gaseous medium in the drying cylinder, the duration and number of cycles, the wood parameters (humidity, temperature, mass), the rate of depressurization, and evacuation.

Examples of the drying kinetics of cylindrical specimens of diameter D = 0.08 m with the initial humidity W_0 = 47.3% and diameter D = 0.1 m, W_0 = 69.2% at a cyclic release of pressure are given in Figs. 2 and 3. Heating in the first drying cycle lasted until the readings of the temperature sensors located at different depths in the wood differed by no more than 2–3^{o}C. In high-temperature drying a change in the color of the wood surface associated with the oxidation processes is usually observed. To remove the surface blackening of specimens, pre-evacuation of the drying chamber and of the wood was carried out.

The data presented in Figs. 2 and 3 illustrate the interrelationship between the temperature of the wood and the pressure of the vapor-air medium in the chamber: the pressure value of the vapor-air medium first increases slowly because of the gradual heating of the entire bulk of the wood and then decreases due to the decrease in the moisture content of the wood. The behavior of the temperature curves in Fig. 3 confirms the fact that at a high temperature wood exhibits a high vapor permeability [12]. When the readings of the thermocouples in the period of intensive vapor formation upon depressurization become much higher than 100^{o}C (in Fig. 3 at $\tau > 450$ min), this points to the absence of a noticeable quantity of free moisture in the specimen. The drying process can be terminated when it is required to dry articles to the transport humidity (W = 18–20%) or for the subsequent deep impregnation, e.g., with the aim of their antiseptic treatment [15]. The data on the humidity of wood upon completion of the experiment and splitting of a specimen of D = 0.1 m have proved this presumption. Measurements by a needle moisture meter have shown that the moisture of the surface layer was 5–7% and that of the central part was 11–14%. As would be expected, the rate of drying a specimen with a smaller diameter and a lower initial humidity (Fig. 2) is much higher.

Despite the considerable spread of the moisture content along the radius of the specimen, the drying quality is good. The absence of noticeable cracks and other drying defects is associated, in our opinion, with the fairly high vapor permeability and plasticity of the wood upon such heat treatment [14]. No marked change in the color of the wood surface connected with the oxidation has been observed. Thus, using preevacuation and prolonged initial heating,



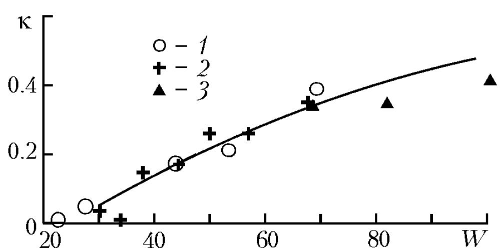


Fig. 4. Measurement data for the volume and surface intensities of drying of cylindrical specimens of wood depending on the duration of the process. I_v, kg/(m^3·h); I, kg/(m^2·h); τ, min.

Fig. 5. Coefficient of thermomechanical removal of moisture in the liquid phase versus the absolute humidity of wood 1) W_0 = 67.7%; 2) 69.2; 3) 100.6. W, %.

TABLE 1. Masses of Vapor and Liquid Entering the Condenser in the First Drying Cycle

W_0, %	m, g	ΔT, °C	m_e, g	m_{liq}, g
67.7	400	26	260	140
69.2	450	31	275	175
100.6	575	33	335	240

one can ensure defect-free drying. The preliminary estimate has shown that in such treatment with increasing temperature in the chamber the wood acquires the qualities obtained by the Thermowood technology [16].

The high rate of the process is evidenced by curve I of the drying intensity versus time given in Fig. 4. The same figure also presents the drying intensity curve I_v pretaining to the bulk of the material which, as we see it, better describes the process of drying wood of a large cross-section (beams, poles, etc.) or other three-dimensional materials. The intensity of moisture removal in the conducted set of experiments reached I = 0.4–0.6 kg/(m^2·h), I_v = 19–22 kg/(m^3·h), which is dozens times higher than in convective drying. The marked maximum on the given curves points to the completion of the process of free moisture removal from the specimens.

To estimate the effect of mechanical removal of moisture from wood, in the condenser simultaneously with measurements of the quantity of incoming moisture we measured the cooling water temperature in each depressurization cycle. In the given run of measurements, a glass spherical flask filled with water was used to collect condensate; the vapor carrying water drops got into the water. The weight of the flask was continuously recorded by a weight meter. The temperature of water was checked by means of thermocouples. The quantity of condensed vapor and dropping liquid was estimated with the use of thermal balance equations with account for the loss due to the heating of the condenser case.

The measurement data have shown that the maximum effect of thermomechanical forcing out of moisture in the form of a liquid was observed in the first cycle of depressurization when the structure of wood cells contains the maximum quantity of free moisture. In this case, the quantity of the ejected liquid phase constituted up to 10% of the total mass of moisture removed from the specimen in the course of the drying process [12, 17]. In the subsequent cycles of depressurization, the fraction of the liquid phase decreases and that of vapor increases. The estimates of the evaporated liquid and dropping moisture removed from the specimen in the first cycle of depressurization for three specimens of diameter D = 0.1 m are given in Table 1.

After three cycles of pressure release the efficiency of the process of heat and mass transfer differed slightly from the conventional high-temperature drying. With increasing moisture content of the wood, the role of the liquid phase in the yield increases, which is illustrated by the results of determining the coefficient of thermomechanical removal of moisture presented in Fig. 5. These data at $W \approx 100\%$ are in good agreement with the data of [7] obtained for the thermomechanical drying of a peat plate with a moisture content of 1 kg/kg, where $\kappa \approx 0.5$.

It should be noted that the results presented demonstrate the effect of removal of moisture in the liquid form (droplets) at a mean absolute humidity of 30% or even less, i.e., to values of the saturation limit of the cellular wall of the wood. This is indicative of the specificity of moisture transfer in wood at high temperatures.

Conclusions. As a result of the investigations made, a high rate of the process of thermomechanical drying of cylindered wood has been attained: upon heating to 140–150^{o}C the drying time was 10–12 h depending on the initial moisture and diameter of specimens. It has been established that the drying intensity in the set of experiments performed reached I = 0.4–0.6 kg/(m^2·h), I_v = 19–22 kg/(m^3·h), which is dozens of times higher than the drying intensity attained in traditional convective drying chambers. The largest quantity of removed moisture in the droplet form is observed in the first drying cycle — up to 10% of the whole of the dried moisture.

The high-temperature thermomechanical method promotes the diffusion and the molar vapor transfer in pores providing low moisture content gradients and, consequently, low stresses in the material, which, as applied to wood, upgrades the drying quality. Noticeable cracks and defects characteristic of intensive convective drying of cylindrical articles are absent. Preevacuation prevents darkening of the surface of specimens.

The proposed method can be recommended for fast and qualitative preimpregnation drying of cylinder-shaped wood before autoclave protective treatment. In this case, the drying time can be reduced to 6–8 h.

NOTATION

D, diameter, m; $I = m_{liq}/S\tau$, $I_v = m_{liq}/V\tau$, surface and volume drying intensity, kg/(m^2·h), kg/(m^3·h); m, mass, g; P, chamber pressure, MPa; r, specimen radius, m; S, surface area, m^2; T, temperature, ^{o}C; V, volume, m^3; W, absolute moisture, %; ΔT, change in the water temperature in the condenser; τ, time, min; $\kappa = m_{liq}/(m_{liq}/m_e)$, coefficient of thermomechanical removal of moisture. Subscripts: 0, initial; liq, liquid; e, vapor; f, final; v, volume.

REFERENCES

1. P. I. Anan'in and V. N. Petri, *High-Temperature Drying of Wood* [in Russian], Goslesbumizdat, Moscow (1963).
2. V. I. Patyakin, Yu. G. Tishin, and S. M. Bazarov, *Technical Hydrodynamics of Wood* [in Russian], Lesnaya Promyshlennost', Moscow (1990).
3. V. P. Kozhin, Experimental investigation of centrifugal dewatering and drying of highly wet wood, in: *Proc. Int. Sci. Conf. "Centrifugal Technique — High Technologies,"* Minsk (2003), pp. 52–57.
4. M. Stahl and M. Bentz, High-pressure treatment of wood — combination of mechanical and thermal drying in "I/D process," *Chem. Eng. Technol.*, **27**, No. 11, 1216–1221 (2004).
5. A. Kh. Mirzadzhanzade, M. M. Khasanov, and R. N. Bakhtizin, *Modeling of the Processes of Oil and Gas Production* [in Russian], ANO Inst. of Computer Studies, Moscow–Izhevsk (2004), p. 367.
6. Yu. A. Mikhailov, *Drying by Superheated Steam* [in Russian], Énergiya, Moscow (1967).
7. A. S. Shteinberg, R. Z. Tseitlina, and I. D. Sokolov, Drying of peat insulating slabs by the depressurization method, *Inzh.-Fiz. Zh.*, **8**, No. 6, 730–734 (1965).
8. Yu. A. Mikhailov, Heat and mass transfer on depressurization, *Inzh.-Fiz. Zh.*, **4**, No. 2, 33–43 (1961).
9. A. V. Luikov, *Theoretical Foundations of Building Thermophysics* [in Russian], Izd. AN BSSR, Minsk (1961), p. 340.
10. A. V. Luikov and Yu. A. Mikhailov, *Theory of Heat and Mass Transfer* [in Russian], Gosénergoizdat, Moscow–Leningrad (1963), pp. 444–454.
11. S. T. Choi, V. P. Golitsyn, N. V. Golitsyna, et. al., *Method of Drying Wood and a System Thereof*, Patent USA # 6,640,462. 2003.
12. N. M. Gorbachev, V. P. Kozhin, B. K. Lovetskii, N. L. Solntseva, and K. G. Chizhik, Experimental investigation of the thermomechanical drying of wood, in: *Heat- and Mass Transfer–2007* [in Russian], Volume of Collected Papers, Minsk (2007), pp. 94–101.
13. V. N. Kuzovov, High-temperature drying of wood in a variable-pressure medium, *Lesnoi Ékspert*, No. 8(21), 36 (2004).
14. S. G. Romanovskii, *Processes of Thermal Treatment and Drying in Electromagnetic Plants* [in Russian], Énergiya, Minsk (1969), p. 129.

15. S. M. Arinkin, V. P. Kozhin, and V. K. Shchitnikov, *Specific Features of the Process of Wood Impregnation and Dependence of Protective Solution Absorption on the Pressure Parameters*, Preprint No. 8 of the A. V. Luikov Institute of Heat and Mass Transfer, Minsk (1999).
16. *Thermowood Handbook*, Finnish Thermowood Association, FIN-00171, Helsinki, Finland (2003).
17. N. M. Gorbachev and V. P. Kozhin, High-temperature thermomechanical drying of wood, in: *Heat- and Mass Transfer–MIF-2008*, *6th Minsk Int. Forum*, 19–23 May 2008, Vol. 2, Minsk (2008), pp. 187–190.